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A Building-Resolved Wind Field Library for Vancouver. Facilitating CBRN Emergency Response for the 2010 Winter Olympic Games

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Technical Memorandum

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June 2010

Canada

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Abstract

This memorandum describes some initial work to construct a wind field library consisting of pre-computed building-aware mean wind and turbulence fields obtained from a high-resolution, high-fidelity computational fluid dynamics (CFD) model for a specific urban area; namely, for the downtown area of Vancouver and the surrounding environs for use in "on-demand" CFD in support of emergency response applications (requiring quick turn-around times) for the 2010 Winter Olympic Games. To this purpose, mean wind and turbulence field simulations were obtained for 32 wind directions using CFD over a model (computational) domain of 255 km^2 (with a building-aware region of 10.4 km^2 at 9-m horizontal resolution) centered on downtown Vancouver. An example illustrating the application of the wind field library for the rapid calculation of urban dispersion for a release of a hazardous material in downtown Vancouver is provided.

Résumé

Ce document décrit certaines recherches préliminaires en vue de la constitution d'une logithèque de champs de vents comprenant des vents moyens et des champs de turbulence préinformatisés dans une région construite, obtenus à l'aide d'un modèle informatique fondé sur la dynamique des fluides numérique (DFN) à haute résolution et à haute fidélité pour une zone urbaine donnée, à savoir le centre ville de Vancouver et les régions environnantes, à utiliser dans des cas de DFN sur demande à l'appui des opérations d'intervention d'urgence (exigeant des délais d'intervention rapides) pour les Jeux olympiques d'hiver 2010. À cette fin, on a obtenu des simulations de vents moyens et de champs de turbulence pour 32 directions de vents en utilisant la DFN sur un domaine de calcul modèle de 255 km^2 (dans une région construite de 10,4 km^2 à résolution horizontale de 9-m) située au centre-ville de Vancouver. Un exemple illustrant l'utilisation d'une logithèque de vents moyens pour le calcul rapide de la dispersion urbaine en cas de libération d'une matière dangereuse au centre ville de Vancouver est fourni.

Executive summary

A Building-Resolved Wind Field Library for Vancouver. Facilitating CBRN Emergency Response for the 2010 Winter Olympic Games

E. Yee, F.-S. Lien, H. Ji; DRDC Suffield TM 2010-088; Defence R&D Canada – Suffield; June 2010.

Background: The release of chemical, biological or radiological (CBR) agents by terrorist or rogue states in a North American city (densely populated urban center) and the subsequent exposure, deposition and contamination are emerging threats in an uncertain world. As a consequence, the understanding of the wind flow in an urban area and the concomitant dispersion of material released into that flow is crucially important. High-resolution, three-dimensional computational fluid dynamics models can accurately simulate complex, highly-disturbed dynamic flows in and around arbitrary building configurations in an urban area and are useful for the prediction of building-to-urban scale transport and dispersion of contaminants released in such flows. Unfortunately, these models are not appropriate for applications where a quick turn-around time is required (e.g., emergency response applications involving the release of a CBR agent in a cityscape).

Principal results: This memorandum describes some initial work to construct a wind field library consisting of pre-computed building-aware mean wind and turbulence fields obtained from a high-resolution, high-fidelity computational fluid dynamics (CFD) model for a specific urban area; namely, for the downtown area of Vancouver and the surrounding environs for use in “on-demand” CFD in support of emergency response applications (requiring quick turn-around times) for the 2010 Winter Olympic Games. To this purpose, mean wind and turbulence field simulations were obtained for 32 wind directions using CFD over a model (computational) domain of 255 km^2 (with a building-aware region of 10.4 km^2 at 9-m horizontal resolution) centered on downtown Vancouver. An example illustrating the application of the wind field library for the rapid calculation of urban dispersion for a release of a hazardous material in downtown Vancouver is provided.

Significance of results: The work reported herein demonstrates for the first time the feasibility of using a building-induced wind field library for a specific (pre-determined) urban area to enable “on-demand” CFD predictions of urban dispersion for emergency response applications that require short turn-around times. This enables the detailed and accurate information on the complex building-induced local flow fields obtained from high-resolution CFD simulations to be used in an operational framework.

Future work: Future work will investigate the application of this methodology to other cities (e.g., generation of a CFD-based wind field library of mean wind and turbulence fields for Toronto to support the upcoming Group of Twenty (G-20) summit which will be hosted by Canada in June 2010). This type of modelling exercise will enable further experience

to be gained in the application of wind field libraries (e.g., to other urban environments consisting of different building configurations and street networks).

Sommaire

A Building-Resolved Wind Field Library for Vancouver. Facilitating CBRN Emergency Response for the 2010 Winter Olympic Games

E. Yee, F.-S. Lien, H. Ji ; DRDC Suffield TM 2010-088 ; R & D pour la défense Canada – Suffield ; juin 2010.

Contexte : La libération d'agents chimiques, biologiques ou radioactifs (CBR) par des États terroristes ou voyous dans une ville de l'Amérique du Nord (centre urbain densément peuplé) et l'exposition, le dépôt et la contamination subséquents constituent de nouvelles menaces dans un monde incertain. Par conséquent, la compréhension du flux de vents dans une zone urbaine et de la dispersion concomitante de la matière libérée dans ce flux est particulièrement importante. Des modèles de dynamique des fluides numérique à haute résolution et tridimensionnels peuvent simuler avec exactitude des flux dynamiques complexes et très perturbés, à l'intérieur et autour de configurations de bâtiments choisies arbitrairement dans une zone urbaine, et ils sont utiles pour prédire le transport et la dispersion en zone bâtie et urbaine de contaminants libérés dans ces flux. Malheureusement, ces modèles ne sont pas appropriés pour les opérations nécessitant un délai d'intervention rapide (p. ex., les opérations d'intervention d'urgence concernant la libération d'un agent CBR en zone urbaine).

Résultats principaux : Ce document décrit certaines recherches préliminaires en vue de la constitution d'une logithèque de champs de vents comprenant des vents moyens et des champs de turbulence préinformatisés dans une région construite, obtenus à l'aide d'un modèle informatique fondé sur la dynamique des fluides numérique (DFN) à haute résolution et à haute fidélité pour une zone urbaine donnée, à savoir le centre-ville de Vancouver et les régions environnantes, à utiliser dans des cas de DFN sur demande à l'appui des opérations d'intervention d'urgence (exigeant des délais d'intervention rapides) pour les Jeux olympiques d'hiver 2010. À cette fin, on a obtenu des simulations de vents moyens et de champs de turbulence pour 32 directions de vents en utilisant la DFN sur un domaine de calcul modèle de 255 km^2 (dans une région construite de 10,4 km^2 à résolution horizontale de 9-m) située au centre-ville de Vancouver. Un exemple illustrant l'utilisation d'une logithèque de vents moyens pour le calcul rapide de la dispersion urbaine en cas de libération d'une matière dangereuse au centre-ville de Vancouver est fourni.

Portée des résultats : Les recherches décrites dans le présent rapport démontrent pour la première fois la faisabilité de l'utilisation d'une logithèque de champs de vents qui sont créés par les bâtiments dans une zone urbaine particulière (prédéterminée), afin de permettre des prédictions de DFN sur demande en cas de dispersion urbaine pour des opérations d'intervention d'urgence nécessitant d'agir rapidement. Cela permet d'utiliser dans un cadre opérationnel des renseignements détaillés et exacts sur les champs de flux de vents complexes créés par les bâtiments localement, qui sont obtenus à l'aide de simulations de DFN à haute résolution.

Perspectives d'avenir : Les recherches futures examineront la possibilité d'utiliser cette méthode pour d'autres villes (p. ex., la production d'une logithèque de champs de vents fondée sur la DFN de vents moyens et de champs de turbulence pour la ville de Toronto, à l'appui du prochain sommet du G-20 qui sera organisé par le Canada en juin 2010. Ce type de modélisation permettra de gagner plus d'expérience dans l'utilisation de logithèques de champs de vents (p. ex., dans d'autres environnements urbains composés de différents réseaux de rues et configurations de bâtiments).

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Acknowledgements

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1 Introduction

The prospect of a terrorist incident involving the airborne release of a chemical, biological or radiological (CBR) agent in a city can potentially cause massive casualties and overwhelm the available emergency facilities. Certainly, the September 11th terrorist attacks on the World Trade Center and the Pentagon served to heighten the fear that people and cities in North America might now be the targets of CBR terrorism. The extent of the region in a built-up environment that might become contaminated following an airborne (accidental or deliberate) release of toxic gases and aerosols and knowledge of the subsequent downwind transport, diffusion, deposition and fate of the contaminant is of great importance for emergency response planning and management, as well as for training personnel (first-responders).

The urban environment, in which a large collection of buildings and other obstacles (e.g., cars lining a street, treed areas in city green spaces, etc.) are aggregated in complex structures, is invariably characterized by particularly complex flow patterns that include curved mean streamlines, sharp velocity discontinuities, large velocity gradients, flow separations and reattachments, cavity regions, recirculating zones, and strongly non-stationary and inhomogeneous turbulence. As a consequence, it should not too surprising that the buildings in an urban environment can significantly alter the transport and dispersion of a pollutant plume and provide nonintuitive concentration distributions (e.g., channeling of winds in a street canyon may cause the plume to travel in a direction opposed to the prevailing wind flow aloft, topological dispersion can result in secondary sources, rapid vertical dispersion can occur for plume material entrained in an updraft downwind of a tall building, etc.).

As a consequence of the complexity of the flow in a cityscape, the development of physically-based urban wind models that can provide the needed spatial-temporal pattern of urban wind statistics required to "drive" the physically-based modelling of the dispersion of contaminants within and above the arbitrary building complex of an urban environment, poses many interesting (and seemingly insuperable) challenges for atmospheric scientists. Because fluid dynamics is the most important physical process involved in the transport and dispersion of toxic materials released in built-up city centers, it is natural that computational fluid dynamics (CFD) has become an increasingly valuable tool for accurately predicting (or, simulating) the complicated dynamic flow in and around the complex geometry that is characteristic of a cityscape. This realization formed the basis for the development of an advanced emergency response system for toxic gas and aerosol hazard prediction and assessment for the urban environment sponsored by **C**hemical, Biological, Radiological-Nuclear and Explosive **R**esearch and **T**echnology **I**nitiative (CRTI) under Project 02-0093RD entitled "An Advanced Emergency Response System for CBRN Hazard Prediction and Assessment for the Urban Environment". This project resulted in the development of a high-fidelity multiscale and multi-physics urban flow and dispersion modelling system that is based on high-resolution, three-dimensional CFD.

The CFD-based modelling system for addressing transport and dispersion in an urban area is a software suite that includes a grid generator, pre- and post-processors, and a

multi-physics control volume pressure-based solver that solves the three-dimensional, time-dependent, incompressible Reynolds-averaged Navier-Stokes (RANS) equations on high-performance parallel computer platforms. The unique features of this specialized modelling suite that facilitate the prediction of urban transport and dispersion include: (1) rapid and high-quality grid generation for the complex geometry in a cityscape directly from building and topography information encoded in digital Geographical Information System (GIS) data; (2) mean wind flow and turbulence field predictions using a distributed parallel solution of the RANS equation based on the Message Passing Interface (MPI), a *de facto* standard for communication among processors that provides a parallel processing implementation ensuring the portability and scalability of the modelling system; and, (3) concentration and/or dosage field predictions using either the solution of an Eulerian-based advection-diffusion equation or of a Lagrangian-based stochastic differential equation.

The high-fidelity multiscale and multi-physics modelling system is very useful for emergency planning, vulnerability assessment, and post-event analysis. However, the CFD-based modelling system requires considerable computational resources and is currently not fast enough to address emergency response applications that require a prompt answer (e.g., in a quick turn-around time of the order of 15 min). As a first real-world test of the urban modelling system to support the Vancouver 2010 Winter Olympic Games for emergency response applications where a quick turn-around time is required, we have investigated the possibility of the construction of a library of pre-computed mean wind and turbulence fields for a large area in downtown Vancouver (encompassing many of the Olympic venues) using our building-resolving CFD-based modelling system.

The primary objective of this memorandum is to describe the compilation of this building-induced wind field library for downtown Vancouver. This wind field library facilitates "on-demand" CFD predictions of flow and dispersion in a prescribed urban area (Vancouver) that can be subsequently utilized in an operational framework. This strategy enables a fast-response time for emergency response applications that require a timely prediction of a toxic agent's spread and deposition in a city, while simultaneously retaining the accuracy and fidelity provided by a state-of-the-science modelling system for incorporating the local effects of the complex urban morphology on contaminant dispersion.

2 Model Configuration

We employ the urban microscale modelling system developed at Waterloo CFD Engineering Consulting Inc. and Defence R&D Canada – Suffield under the sponsorship of CRTI Project 02-0093RD. This modelling system is fully described by Yee et al [1], Yee and Hogue [2] and Lien et al [3] and, as a consequence, only a very brief overview of the system will be presented here. The urban microscale modelling system consists of four main modules: urbanGRID, urbanSTREAM, urbanEU and urbanPOST.

In the simplest terms, urbanGRID imports building information contained in Environmental Systems Research Institute (ESRI) ArcView Shapefiles and uses this data to generate a structured grid over a user-selected computational domain in a given cityscape. In addition

to high-resolution building data encoded in the ShapeFiles, urbanGRID can automatically generate a body-fitted (curvilinear) grid (viz., a grid that follows closely the boundaries defined by the physical space) to accommodate a digital representation of the ground surface topography or terrain in the form of a digital elevation model (DEM). The main advantage of this approach is that the flow can be resolved very accurately at the boundaries of the variable terrain, which is essential in the case of shear layers along these solid boundaries. Finally, urbanGRID can either import three-dimensional meteorological fields provided by a mesoscale model or use simple analytical mean wind and turbulence profiles for specification of the inflow boundary conditions for the urban microscale flow model. As such, the urban microscale flow model can be executed in a stand-alone mode or coupled to a mesoscale model (such as the Canadian Meteorological Centre's large-scale environmental flow model GEM LAM, an acronym which refers to "the **G**lobal **E**nvironmental **M**ultiscale model which encompasses **L**ocal **A**rea **M**odelling").

The structured grid and inflow boundary conditions provided by urbanGRID are used as input by urbanSTREAM, which is a CFD model for the numerical simulation of the flows around and within the complex geometry of buildings in a cityscape. The model solves the high Reynolds number unsteady form of the RANS equations with two forms for the turbulence closure model; namely, the standard k-ϵ model (k is the turbulence kinetic energy and ϵ is the viscous dissipation rate) and the limited-length-scale k-ϵ model proposed by Apsley and Castro [4]. Note that urbanSTREAM, being an unsteady RANS (URANS) model, can respond to time-dependent boundary conditions provided by a mesoscale model, whose spatial and temporal variability mimic the realistic variability expected in atmospheric flows.

The governing equations for the flow are solved using a collocated, pressure-based, finite-volume method. Advective fluxes across a cell face are discretized using a total-variation diminishing (TVD) variant of a third-order upwind discretization scheme known as the Upwind Monotonic Interpolation for Scalar Transport (UMIST) scheme [5]. The physical diffusive fluxes across a cell face are discretized using a standard second-order central differencing scheme. The two iterative schemes available in urbanSTREAM to enforce mass conservation through the pressure-correction algorithm are the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) described in detail by Patankar [6] and the SIMPLEC (SIMPLE-Consistent) algorithm of Van Doormal and Raithby [7]. In conjunction with the collocated grid arrangement used here, this method is known to result in 'pressure checkerboarding' unless special care is taken. Here, the approach of Rhie and Chow [8] is followed to ensure strong coupling between the pressure and velocity fields. The discretized equations corresponding to the transport equations for the mean momentum and turbulence and to the pressure-correction equation were solved using an iterative method called the strongly implicit procedure (SIP) proposed by Stone [9].

The flow solver urbanSTREAM provides the high-resolution wind and turbulence fields used by the Eulerian grid dispersion model urbanEU to simulate the dispersion of contaminants in the urban domain. This model solves the transport equation for the mean concentration of a scalar (contaminant), which assumes the form of an advection-diffusion equation following the use of a gradient diffusion hypothesis for closure of the turbulent concentration fluxes. The turbulent diffusivity K_t that appears in this simple closure model is obtained from

the turbulent viscosity ν_t (predicted by urbanSTREAM) in combination with a turbulent Schmidt number Sc_t in the following manner: $K_t = \nu_t/\mathrm{Sc}_t$. In urbanEU, we use a constant turbulent Schmidt number Sc_t with a value of 0.63.

The dry deposition of materials to surfaces is modelled in urbanEU by imposing the following boundary condition at all solid boundaries (e.g., ground surface, walls and roofs of buildings, etc.) in the computational domain: $K_t \partial C/\partial n + (\mathbf{v_g} + \mathbf{v_d}) \cdot \mathbf{n} \int C\,dt = 0$, where C is the mean concentration, t is time, $\mathbf{v}_g$ is the gravitational settling (or, terminal) velocity, $\mathbf{v}_d$ is the dry deposition velocity and $\mathbf{n}$ is the outward normal vector to the solid surface (with n referring to the direction normal to the solid boundary).

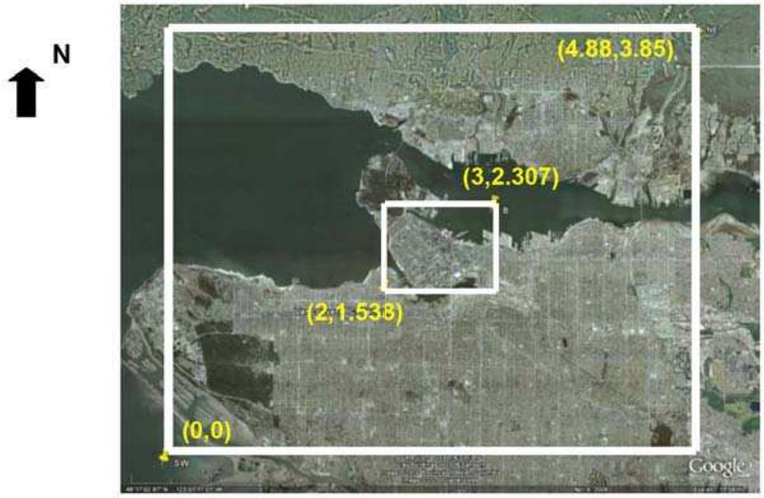
The (particle) size-resolved dry deposition velocity, which includes the effects of aerodynamic resistance, quasi-laminar sublayer resistance and the burst effect of atmospheric turbulence, is parameterized in accordance to the model proposed by Feng [10]. The main physical mechanisms that contribute to the quasi-laminar sublayer resistance include Brownian diffusion, inertial impaction and gravitational sedimentation. The "burst effect of turbulence", which is sometimes referred to as turbophoresis, refers to the tendency of particles to drift towards the direction of decreasing turbulence (viz., down the gradient of the root-mean-square of the turbulent velocity fluctuations). More specifically, because the near-surface turbulence is strongly inhomogeneous, the physical effect of turbophoresis is that the gradients of turbulent velocity near a surface tend to drive the particles towards the surface (recall that owing to the no-slip and impermeability condition at a solid surface, the turbulent (fluctuating) velocities must necessarily decrease to zero as the surface is approached).

Finally, the module urbanPOST is the post-processor. This module is used to process the primary output files from urbanSTREAM to provide the appropriate specification of wind statistics required as input to the Eulerian urban dispersion model urbanEU.

3 Model Domain and Grid Generation

The model (or, computational) domain utilized in this study encompasses a downtown portion of Vancouver, British Columbia. The model domain with the extent of 17,982 m (wide) × 14,155 m (deep) × 1,500 m (tall) in the x- (or, W-E), y- (or, S-N) and z- (or vertical) directions, respectively, covers practically the entire central business district (downtown) of Vancouver and the surrounding environs. The southwest corner (x_0, y_0) of the model domain (see Figure 1) is at the following coordinates in the Universal Transverse Mercator (UTM) coordinate system: zone = 10, x_0 = 481,918.264 UTM easting and $y_0 = 5,451{,}820.269$ UTM northing (or, equivalently, in the geodetic coordinate system this location is 49° 13′ 8″ N and 123° 14′ 53″ W).

The internal coordinate system used in urbanSTREAM is shown in Figure 1(a), where the southwest corner of the modelling region is chosen as the origin $(0, 0)$ in the x-y (horizontal) plane. All distances shown here have been normalized by a reference length scale which is chosen in this case to be $\Lambda_{\mathrm{ref}} = 3681.124$ m. Hence, in this internal coordinate system, the



(a) Model domain

(b) Building-resolved region

Figure 1: *(a) Model domain used for the simulation of the disturbed flow in Vancouver and the surrounding environs [©2008 Google, Gray Buildings ©2008 Sanborn, Image ©2010 Province of British Columbia] b) Expanded view of the interior building-resolved region in the model domain [©2008 Google, Gray Buildings ©2008 Sanborn, Image ©2010 Province of British Columbia].*

northeast corner of the model domain is referenced as $(4.88, 3.85)$. A proper subset within the model domain is chosen as the region in which buildings will be explicitly resolved in the flow simulation. For this study, this rectangular building-resolved region with horizontal extent (3,681.124 m $\times$ 2,830.999 m) has its southwest corner at (2, 1.538) and its northeast corner at (3, 2.307) in the internal coordinate system. This is demarcated as the inner rectangle in Figure 1(a) and an expanded view of this building-resolved region is exhibited in Figure 1(b). In the portion of the model domain lying outside the building-resolved region, all buildings are treated as virtual and their effects on the flow are modelled using

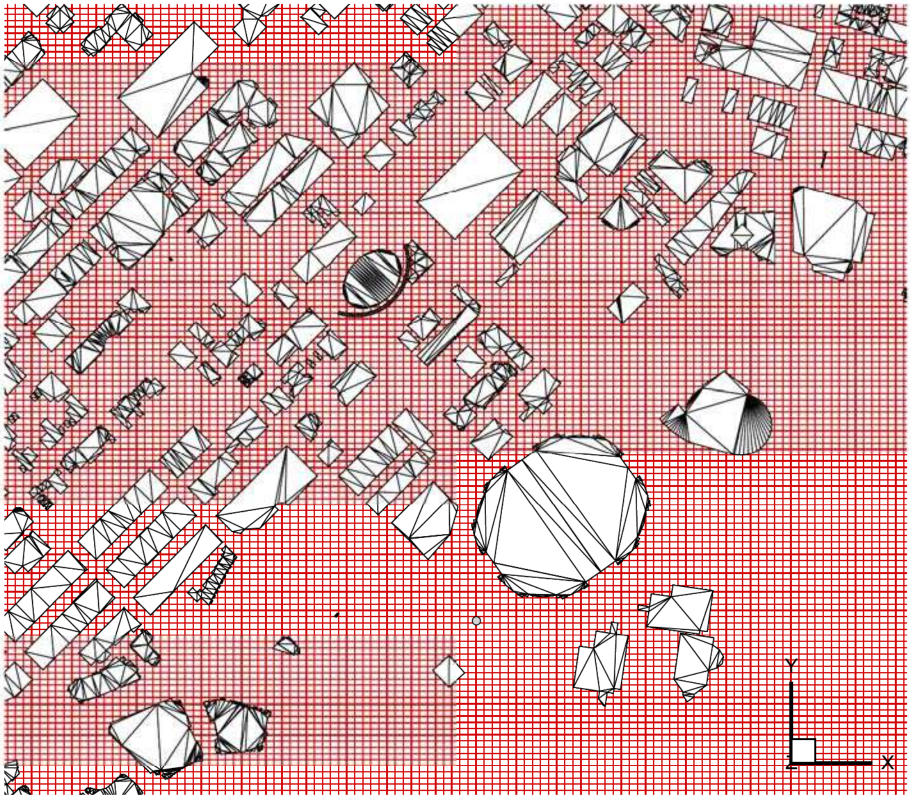


Figure 2: *A sub-region of the building-resolved region showing the fine computational grid generated by urbanGRID.*

a distributed drag force representation in the mean momentum equations.

ESRI ArcView Shapefiles that describe the shapes, locations and heights of buildings in downtown Vancouver and a DEM for Vancouver and the surrounding environs were used in urbanGRID to generate automatically a terrain-fitted grid mesh over the model domain. The DEM for Vancouver and the surrounding area (with a spatial resolution of up to 0.75 arc seconds) was taken from GeoBase, which archives a comprehensive and current database of geospatial data for all of Canada [11]. The terrain-fitted grid system with curvilinear coordinates ξ^i $(i = 1, 2, 3)$ is chosen so as to simplify the functional equation that defines the topography of the ground surface: instead of describing the terrain by the implicit equation $\mathcal{B}(x^i) = 0$ in a Cartesian coordinate system (where x^i $(i = 1, 2, 3)$ are the Cartesian coordinates), the ground topography is defined simply by $\xi^3 = 0$. The simulation is carried out in the three-dimensional computational space defined by the curvilinear coordinate system, and curved surfaces on buildings or planar building surfaces that are not aligned with the grid lines in the computational space are approximated by stepwise surfaces.

A mesh of $380 \times 380 \times 70$ grid lines in the x-, y-, and z-directions, respectively, was used to accommodate all the necessary geometrical details. The interior building-resolved region of the model domain was covered with a fine calculation grid of $320 \times 320 \times 70$ grid lines

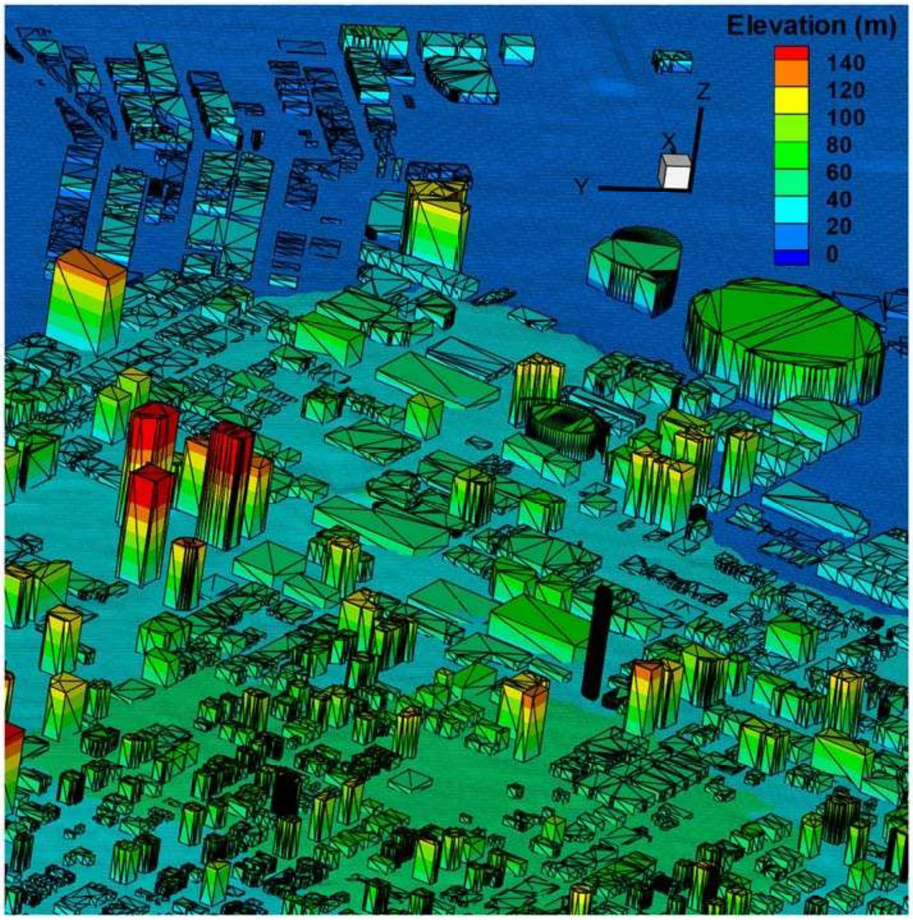


***Figure 3:** A plot showing the elevation of the ground topography and building height referenced relative to mean sea level for a portion of downtown Vancouver lying within the building-aware region of the model domain.*

to better approximate the building features in this region. The grid arrangement adopted here is shown in the x-y plane for a small sub-region of the building-resolved region in Figure 2. The sub-region shown here is centered (approximately or better) about BC Place stadium (which is the official ceremonies venue for the 2010 Olympic and Paralympic Winter Games). Note that the buildings in this area are irregularly spaced and had variable height (see Figure 3 which exhibits the height of the ground topography and the buildings above mean sea level), and many were irregularly shaped. The fine grid used for the building-resolved region contains 7,168,000 nodes, whereas the entire computational domain was covered with a mesh of 10,108,000 nodes. As such, the buildings in the interior building-aware region of the model domain were resolved with a horizontal resolution of about 9 m and a vertical resolution of about 4 m.

The grid lines generated by urbanGRID for the computational domain were preferentially concentrated near the solid surfaces (ground, building rooftops and walls) where the gra-

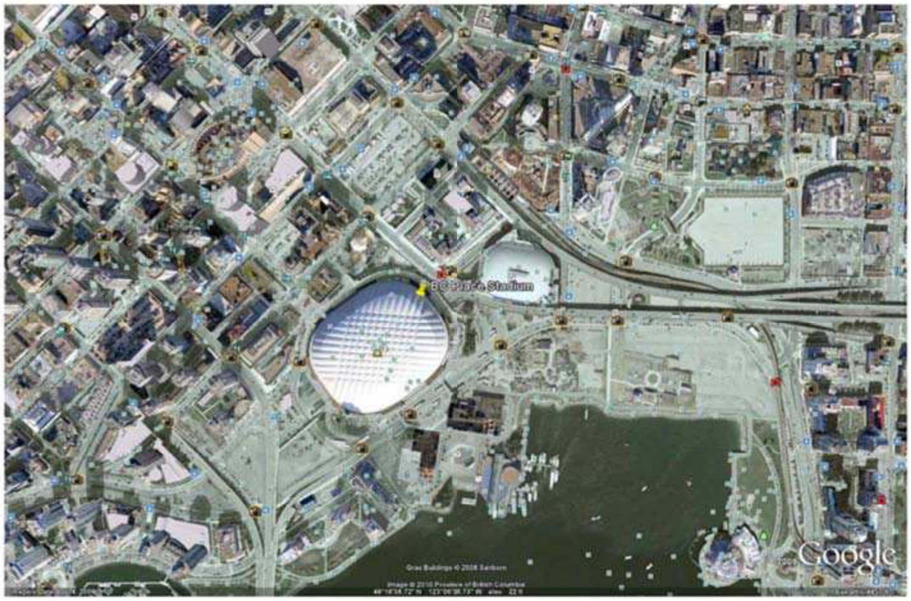


Figure 4: *A satellite photograph (image) of a portion of downtown Vancouver centered approximately about BC Place stadium [©2009 Google, Gray Buildings ©2008 Sanborn, Image ©2010 Province of British Columbia].*

dients in the flow properties are expected to be greatest, and the spacing between the grid lines was gently stretched with increasing distance either outside the building-region (viz., in the virtual building region where the effects of the buildings on the flow were represented using a drag force approximation) and/or above the ground surface. Figures 2 and 3 show the finite-volume approximation of some of the explicitly resolved buildings in the building-aware region, and these approximated buildings should be compared to the actual (true) buildings in this area given in Figure 4 in the form of a satellite photograph (obtained April 4, 2009). As can be seen, there is very little difference between the finite-volume approximated buildings and the actual (true) buildings and therefore the stepwise approximation of the building surfaces is not expected to undermine the accuracy of the subsequent flow simulation.

4 Wind Field Library Generation

To generate the wind field library for Vancouver and the surrounding environs, the CFD model urbanSTREAM was executed in a stand-alone mode [viz., this flow model was not coupled to a mesoscale (or, large-scale environmental flow) model]. In consequence, at the inflow (inlet) boundary of the computational domain [shown in Figure 1(a)] a power-law velocity profile corresponding to neutral stability was used to define the inflow boundary conditions for the simulations. The power-law profile was constructed with a reference wind speed of $U_{10} = 2.235$ m s^{-1} at 10-m height above ground level and with a power-law coefficient of $p = 0.3$ (which is appropriate for a suburban area). For the wind field library

Table 1: *Summary of the wind directions used to generate the wind field library, and the total CPU time required for the simulation for each wind direction.*

Wind Direction (°)	Designation	CPU Time (s)
0.0	N	712,270
11.25	NNNE	817,266
22.5	NNE	633,831
33.75	ENNE	718,765
45.0	NE	733,765
56.25	NENE	810,747
67.5	ENE	725,494
78.25	EENE	989,411
90.0	E	815,154
101.25	EESE	928,507
112.5	ESE	698,276
123.75	SESE	756,679
135.0	SE	682,964
146.25	ESSE	693,273
157.5	SSE	570,144
168.75	SSSE	812,015
180.0	S	612,570
191.25	SSSW	556,571
202.5	SSW	637,727
213.75	WSSW	759,288
225.0	SW	692,348
236.25	SWSW	828,798
247.5	WSW	778,028
258.75	WWSW	952,991
270.0	W	852,044
281.25	WWNW	1,034,516
292.5	WNW	772,128
303.75	NWNW	842,743
315.0	NW	619,366
326.25	WNNW	776,438
337.5	NNW	669,525
348.75	NNNW	823,186

generation, simulations were carried out for 32 prevailing (cardinal) wind directions, with a wind direction interval of 11.25°. The wind directions used are summarized in Table 1, along with the designation for each wind direction.

For each simulation, the computational time step was 30 s and the number of time steps taken was 50 to give a total simulation time of 1,500 s (with each time step limited to a

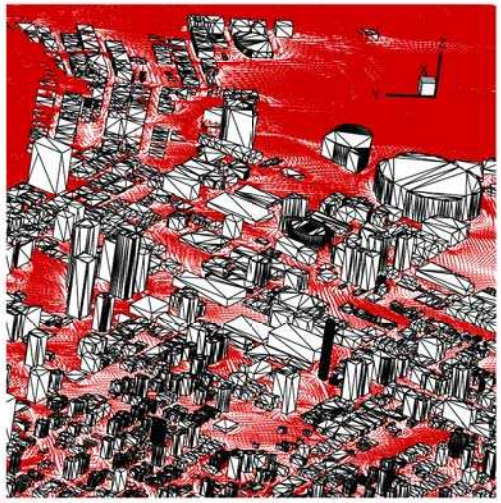
maximum of 250 iterations of the SIMPLE algorithm). The urbanSTREAM simulation of the wind flow over a model domain of 255 km^2 (with a building-aware region of 10.4 km^2 at 9-m horizontal resolution) is expected to take considerable computational time. In consequence, each of the simulations was executed on a parallel computational platform using 16 dedicated processors.

The simulations for the 32 wind directions were undertaken on the SAW computer cluster, which forms part of the grid of high-computational performance clusters that comprise the Shared Hierarchical Academic Research Computing Network (SHARCNET) [12]. The SAW computer cluster consists of a group of 2,704 64-bit high-performance Xeon processors (2.83 GHz clock rate), each of which has 16-GB of local random access memory (RAM), that are linked together with a high-speed InfiniBand interconnection. The total central processing unit (CPU) time required to complete each simulation using 16 processors on SAW is summarized in Table 1. Note that the total CPU time is the sum of the CPU times for all of the 16 processors used for the simulation. On average, each simulation required about 13 h of physical time to complete and the generation of the wind field library, consisting of results from the simulations for the 32 wind directions, was completed in about 4 d. The relatively short physical time for the generation of the wind field library was made possible by the fact that 64 processors on the SAW computing cluster were reserved and dedicated to this task (which, in turn, was made possible by a Small Dedicated Resources award to the authors by SHARCNET).

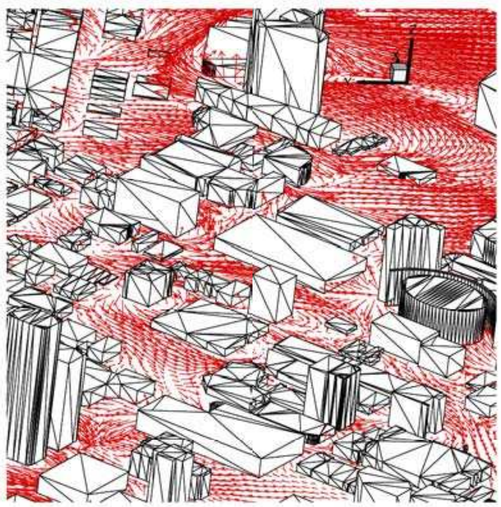
Figure 5 displays the mean flow field for the case with the wind direction at 45° (wind from the northeast (NE)). This figure shows the mean wind velocity vectors on a near-surface horizontal plane at 1.7 m above ground level for a large area within the building-aware region (cf. Figure 5(a)) and for a smaller and expanded region within this large area (cf. Figure 5(b)). Note that the presence of the various buildings strongly perturb the mean velocities (wind speed and direction) away from the undisturbed wind with a uniform direction of 45°.

Generally, there is a very complex swirling flow in the wakes of the various buildings in the building-aware region. The flows around these buildings (especially the shorter buildings) tend to wrap around these obstructions, producing a recirculating flow in the wakes of the obstructions. In certain regions, there is a channelling (or, jetting) of the flow in the narrow alleys (street canyons) between two rows of buildings. For some of the taller buildings, there is an even more dramatic modification of the mean flow field from the ideal case of an undisturbed flow. For some of the taller buildings, one observes the formation of a large spiral vortex (with vertical vorticity) forming on the downwind side of these buildings. This vortex is associated with winds flowing up the downwind side of these taller buildings, leading to updrafts that are expected to have a profound influence on the vertical mixing of a contaminant released into the urban area.

Figure 6 displays the mean wind velocity vectors (wind speed and direction) for an incident wind direction (at the inflow boundary) of 315° (prevailing wind from the northwest (NW)). Again, this figure demonstrates the complexity of the building-induced mean flow field. A comparison of Figure 6 with Figure 5 shows that many of the topological features are similar.



(a) Large area

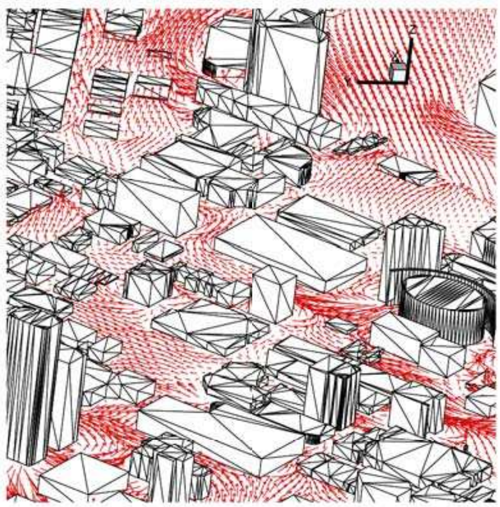


(b) Small area

Figure 5: *Mean wind velocity vectors on a horizontal plane at 1.7 m above ground level for (a) a large area in the building-aware region and (b) an expanded view over a smaller area of the building-aware region of downtown Vancouver. This example corresponds to the building-induced mean flow field resulting from a wind direction of 45° (NE wind) at the inflow boundary of the model domain.*

However, the detailed pattern of the mean wind flow is quite different between the two cases, and this difference will of course lead to quite different concentration patterns for the release of a contaminant at a given location. More specifically, note the significant differences in the channelling of the mean flow between the buildings for the two different wind directions. Indeed, for the wind direction at 45° note that there is a prominent divergence zone in the mean flow field directly northwest of the oval-shaped building (Vancouver Public Library)

(a) Large area

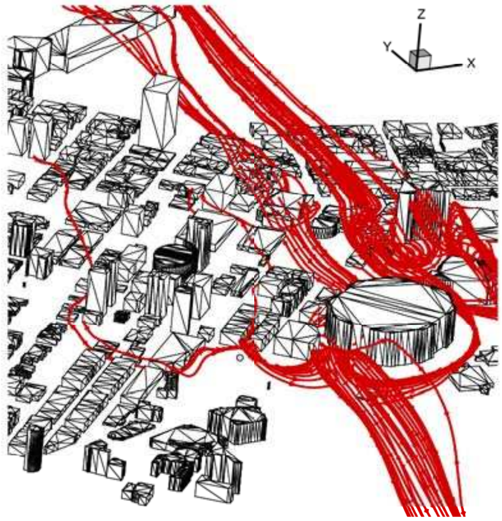


(b) Small area

Figure 6: *Mean wind velocity vectors on a horizontal plane at 1.7 m above ground level for (a) a large area in the building-aware region and (b) an expanded view over a smaller area of the building-aware region of downtown Vancouver. This example corresponds to the building-induced mean flow field resulting from a wind direction of 315° (NW wind) at the inflow boundary of the model domain.*

on the eastern edge of the small area depicted in Figure 5(b). In sharp contrast, for the wind direction at 315° there is instead a strong convergence zone in the mean velocity field directly northwest of the Vancouver Public Library (cf. Figure 6(b)) as the wind is channeled around the northwest side of this building.

To further contrast the significant differences in the mean wind field patterns, Figure 7



(a) Wind direction 45°

(b) Wind direction 315°

Figure 7: *Streamlines (or, streamtraces) of the complicated flow around BC Place stadium for an incident wind direction at (a) 45° and (b) 315°.*

shows a number of streamlines (or, streamtraces) illustrating the complexity of the flow around BC Place stadium for incident wind directions of 45° and 315°. The figure shows streamlines starting at various points in the flow for the two incident wind directions. Note that the streamline images of Figure 7 nicely reveal the complex three-dimensional vortical patterns forming around BC Place stadium. For a wind direction of 45° shown in Figure 7(a), the streamlines around BC Palace stadium exhibit very complicated vortical motions arising from the wake recirculation zone of the tall building directly to the northeast of the stadium. In contrast, for an incident wind direction of 315°, the streamlines diverge

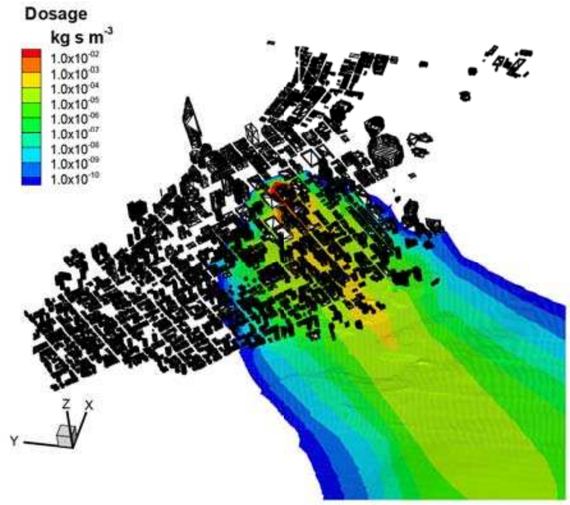
around the windward side of the stadium. Note that even here, the flow skims across the roofs of the buildings on the windward side of BC Place stadium (which are generally smaller in height than the stadium), hits the windward side of the stadium above the heights of these smaller buildings and is deflected downward to create a region of reverse flow in front of the stadium.

5 Application of Wind Field Library to Urban Dispersion

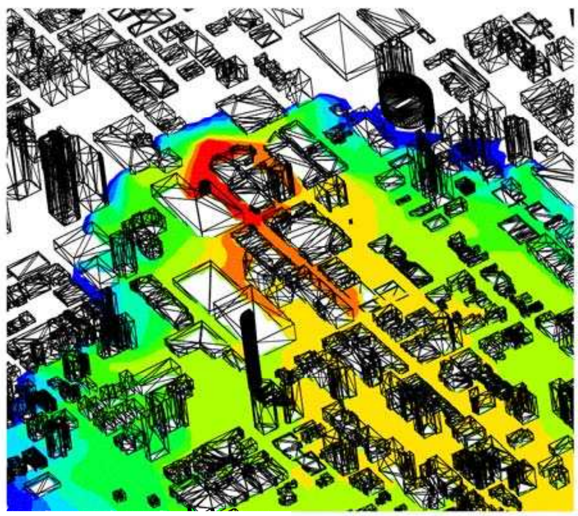
Once the high-resolution CFD-based wind field library for Vancouver has been constructed, the pre-computed mean wind and turbulence fields in this library can be used to "drive" a building-aware urban dispersion model to predict the transport, diffusion, and deposition of a contaminant released in this city. Airflow in an urban area is extremely complicated (see Figures 5 and 6), and this complexity (embodied as such in flow features such as flow separations, stagnation zones, high-velocity jets in street canyons, updrafts in the lee of tall buildings) will undoubtedly influence concentration patterns produced as the result of the release of a contaminant in the urban environment.

To illustrate the application of the wind field library to urban dispersion in downtown Vancouver, let us consider the following example. To this purpose, the flow field statistics for a prevailing wind direction of 45° were extracted from the wind field library and used to "drive" the Eulerian-based urban dispersion model urbanEU. The release (hypothetical only) consisted of 20-kg of the nerve agent sarin (GB), which was disseminated from a stationary truck-mounted sprayer at the following location in downtown Vancouver: 49° 16′ 56″ N latitude and 123° 7′ 2″ W longitude (or, equivalently, at 491,472 UTM easting and 5,458,860 UTM northing in zone 10). This location is roughly on the east side of West Georgia Street near the Scotia Bank Tower in downtown Vancouver. The nerve agent is disseminated in 30 s from the sprayer with a particle size distribution having a mode at 10 μm. This particle size distribution was approximated using seven particle size bins with the centers of the bins located at the following particle diameters: 2.5, 5.0, 7.5, 10.0, 12.5, 15.0 and 17.5 μm. The mass fraction of GB contained in these seven particle bins are, respectively, as follows: 0.075, 0.10, 0.15, 0.35, 0.15, 0.10 and 0.075.

For the simulation of the urban dispersion, the computational time step used in urbanEU is 2.5 s and 600 time steps were taken to give a total simulation time of 1500 s (25 min). Figure 8 displays various isopleths of the predicted near-surface dosage (time-integrated concentration) in the horizontal plane at 1.7 m above ground level in the building-resolved region of the model domain for an incident wind direction of 45°. The complexity of the dosage pattern exhibited here is a direct reflection of the complexity of the disturbed wind field pattern shown earlier in Figure 5. Note that the mean plume centerline appears generally to follow that of the prevailing wind direction above the urban canopy (45° in this case), but the presence of the various buildings has a significant local effect on the dosage contours.



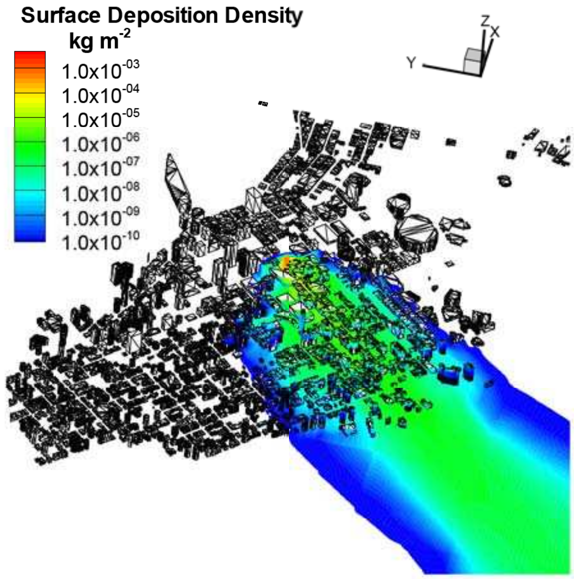
(a) Large area



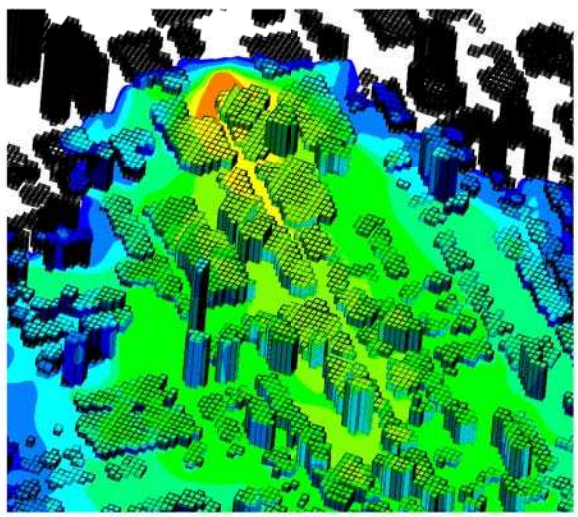
(b) Small area

Figure 8: *Near-surface dosage isopleths in the horizontal plane at 1.7 m above ground level for (a) a large area in the building-aware region and (b) an expanded view over a smaller area of the building-aware region of downtown Vancouver. The results are obtained for a prevailing wind direction of 45°.*

Interestingly, there is a pronounced asymmetry in the dosage isopleths near the source as is clearly evident from an expanded view of the contours displayed in Figure 8(b). For this release, note that there is upwind dispersion in the street network (viz., transport and diffusion in a direction directly opposed to the prevailing wind direction aloft) as well as significant lateral dispersion as the contaminant material is forced around the sides of the buildings. More specifically, the contaminant at street level initially spreads about a block upwind of the release and about two blocks in the lateral direction on each side of the release, before it begins to spread downwind as a broad plume.



(a) Large area



(b) Small area

Figure 9: *Isopleths of the surface deposition density on the ground surface, as well as on the roofs and walls of the buildings for (a) a large area in the building-aware region and (b) an expanded view over a smaller area of the building-aware region of downtown Vancouver. The results are obtained for a prevailing wind direction of 45°.*

Toxic corridors for a contaminant can be obtained from the results shown in Figure 8, once the toxicity levels of the contaminant are specified. For the example given here, where the contaminant is sarin, the relevant toxicity levels are as follows: $\mathrm{LCt}_{50} = 0.75 \times 10^{-6}$ kg s m^{-3} (lethal dosage level that will kill 50% of the exposed personnel); severe $\mathrm{ICt}_{50} = 0.42 \times 10^{-6}$ kg s m^{-3} (incapacitation dosage level that will incapacitate 50% of the exposed personnel); and, mild $\mathrm{ECt}_{50} = 0.0083 \times 10^{-6}$ kg s m^{-3} (effective dosage level that will cause mild (and, reversible) effects in the exposed personnel).

In addition to the dosage, urbanEU also predicts the surface deposition density pattern resulting from the release of the contaminant. Figure 9 displays contours of the surface deposition density on the ground surface and on the walls and roofs of the buildings in the building-aware region of downtown Vancouver. Not surprisingly, the surface deposition density patterns are similar to the dosage patterns exhibited in Figure 8. It is noted that the updrafts on the lee sides of the tall buildings in the urban area result in an upward-directed “chimney effect” on the plume dispersion which mixes the contaminant material in the vertical direction rapidly. In consequence, the contaminant material can be transported rapidly by this chimney effect to the roofs of even very tall buildings, with some of the material subsequently deposited there. A knowledge of the pattern and magnitude of the surface deposition density in a built-up area is very important for emergency response decisions, and further analysis of dispersion model products such as Figure 9 should facilitate the formulation of improved strategies for the decontamination of residual contaminant material deposited on various surfaces (horizontal and vertical) in the urban environment for post-event mitigation.

6 Conclusions

In this memorandum, we have demonstrated how to generate a building-induced wind field library for a large area in downtown Vancouver and how to use this library for pre-event planning, emergency response application, and post-event assessment. In particular, the work reported herein represents the first attempt to construct and use an extensive library of pre-computed mean wind and turbulence fields obtained from very high-resolution, high-fidelity CFD simulations to support emergency response applications in an event of international significance (e.g., the 2010 Winter Olympic Games). The compilation of a CFD-generated building-aware wind field library for Vancouver enables the computationally expensive, but detailed and accurate information on three-dimensional flow patterns in complex built-up environments, obtained from CFD to be used for emergency response applications requiring short turn-around times. In effect, the work reported herein suggests that with the construction of a wind field library for a particular urban area, on-demand CFD can be applied to support emergency response applications in a timely fashion.

In this work, we have only introduced the basic concept of using a wind field library to support CBRN emergency response for Vancouver. Future work will investigate the application of this methodology to other cities (e.g., generation of a CFD-based wind field library of mean wind and turbulence fields for Toronto to support the upcoming Group of Twenty (G-20) summit which will be hosted by Canada in June 2010). This type of modelling exercise will enable further experience to be gained in the application of wind field libraries (e.g., to other urban environments consisting of different building configurations and street networks).

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This memorandum describes some initial work to construct a wind field library consisting of pre-computed building-aware mean wind and turbulence fields obtained from a high-resolution, high-fidelity computational fluid dynamics (CFD) model for a specific urban area; namely, for the downtown area of Vancouver and the surrounding environs for use in "on-demand" CFD in support of emergency response applications (requiring quick turn-around times) for the 2010 Winter Olympic Games. To this purpose, mean wind and turbulence field simulations were obtained for 32 wind directions using CFD over a model (computational) domain of 255 km^2 (with a building-aware region of 10.4 km^2 at 9-m horizontal resolution) centered on downtown Vancouver. An example illustrating the application of the wind field library for the rapid calculation of urban dispersion for a release of a hazardous material in downtown Vancouver is provided.

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